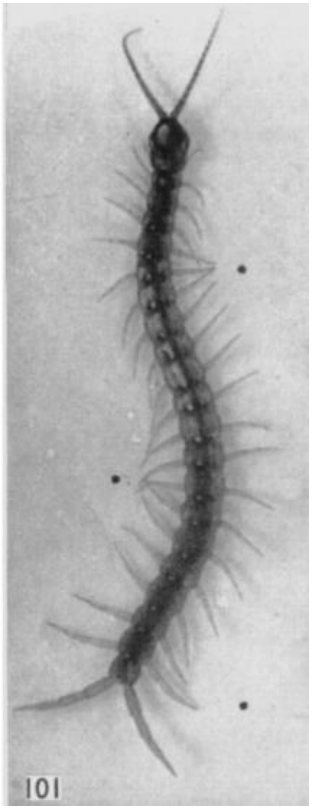
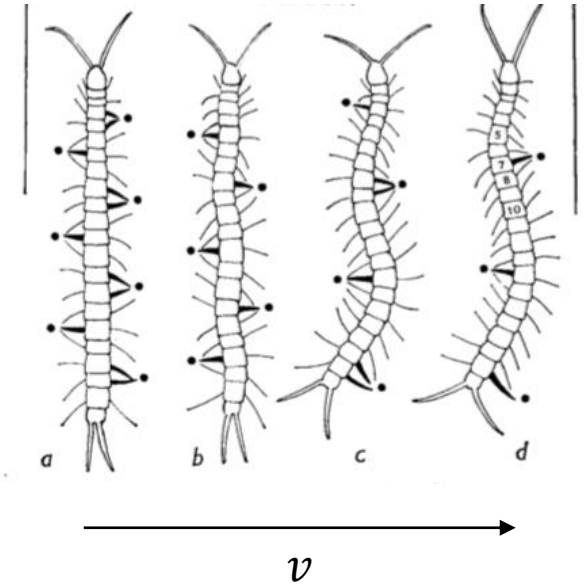
# Motivation

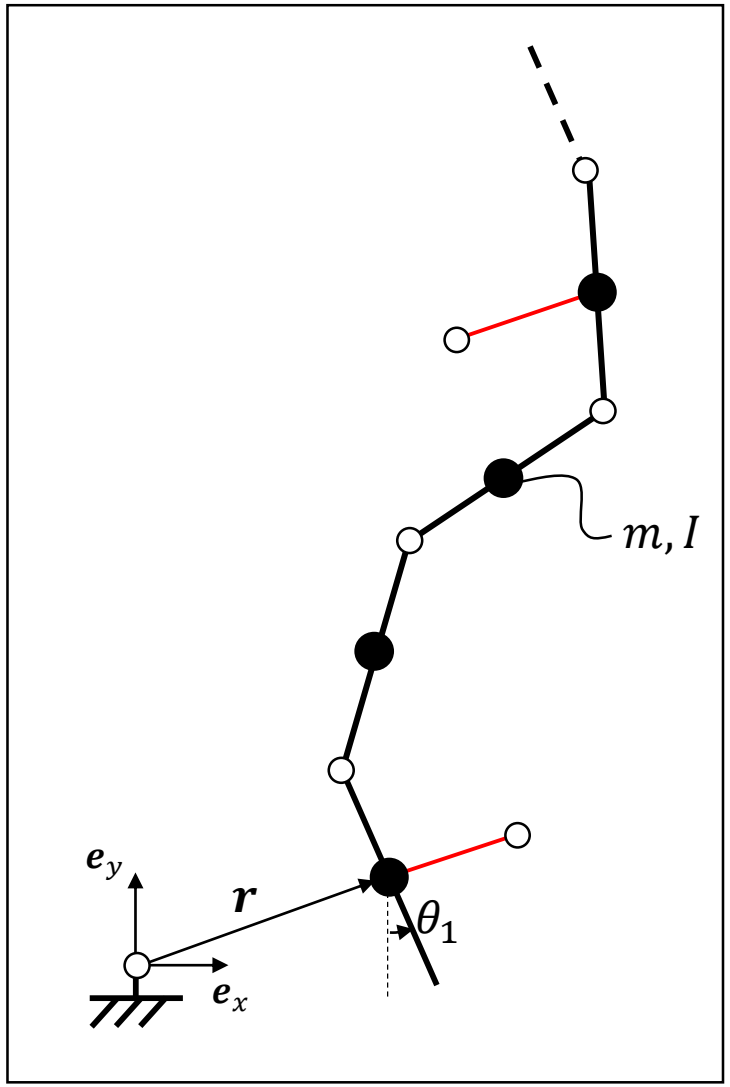



- (Manton, 1977): Undulations are due to stepping pattern and deleterious[1]
- (Anderson, 1995): Undulations actively supported by muscles[2]

Fig. S. M. Manton, Zool. J. Linnean. Soc. 45, 306-07 (1965).
1 S. M. Manton, Oxford: Clarendon Press (1977).
2 B. D. Anderson, J. W. Shultz, and B. C. Jayne, J. Exp. Biol. 198, 1185 (1995).

# Model




- Chain of 21 rigid bodies in transverse plane

$$\mathbf{M}\ddot{\boldsymbol{q}} = \boldsymbol{F} + \mathbf{J}_c^T\boldsymbol{\lambda}$$

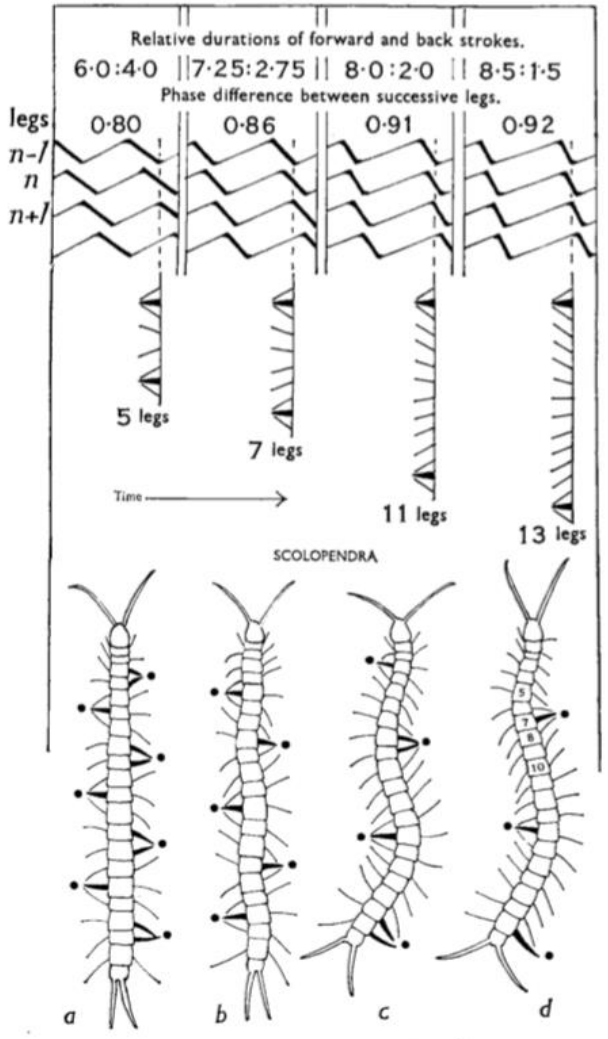
$$\boldsymbol{\lambda} = -(\mathbf{J}_c\mathbf{M}^{-1}\mathbf{J}_c^T)^{-1}(\mathbf{J}_c\mathbf{M}^{-1}\boldsymbol{F} + \boldsymbol{\xi})$$

- Massless legs
- Inelastic impact upon foot placement

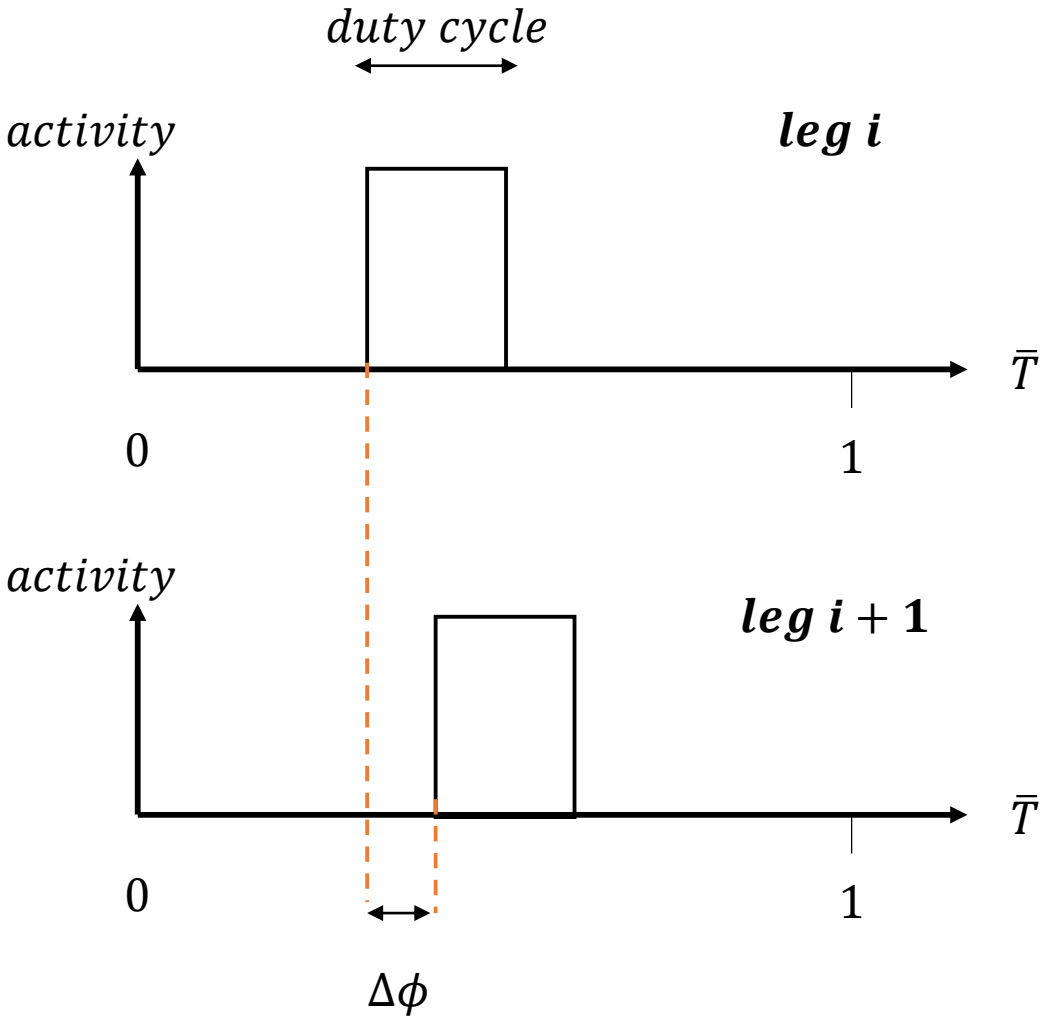
$$\boldsymbol{u}^+ = [\mathbf{I} - \mathbf{M}^{-1}\mathbf{J}_c^T(\mathbf{J}_c\mathbf{M}^{-1}\mathbf{J}_c^T)^{-1}\mathbf{J}_c]\boldsymbol{u}^-$$

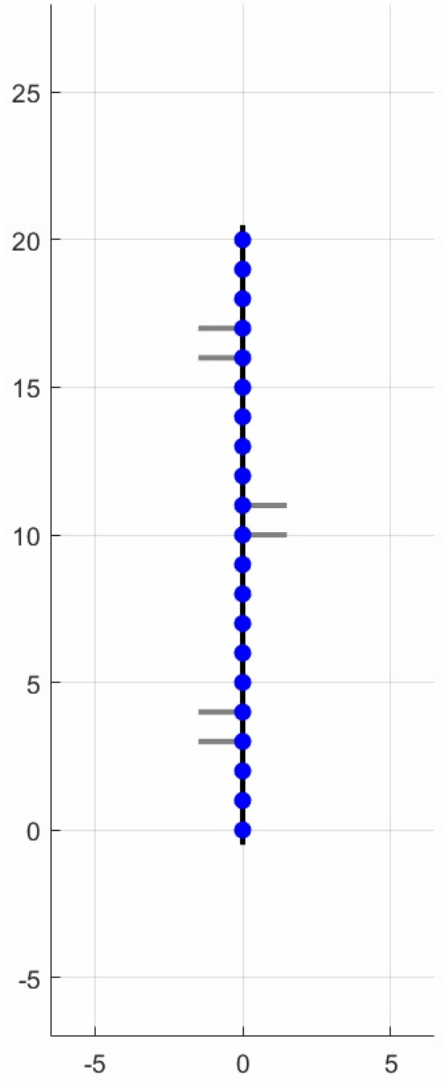
- No-slip condition at footholds
- Non-dimensional representation $(\bar{I}, \bar{T}, \bar{k}, \bar{d})$ by $(m, l, f)$

# Leg kinematics

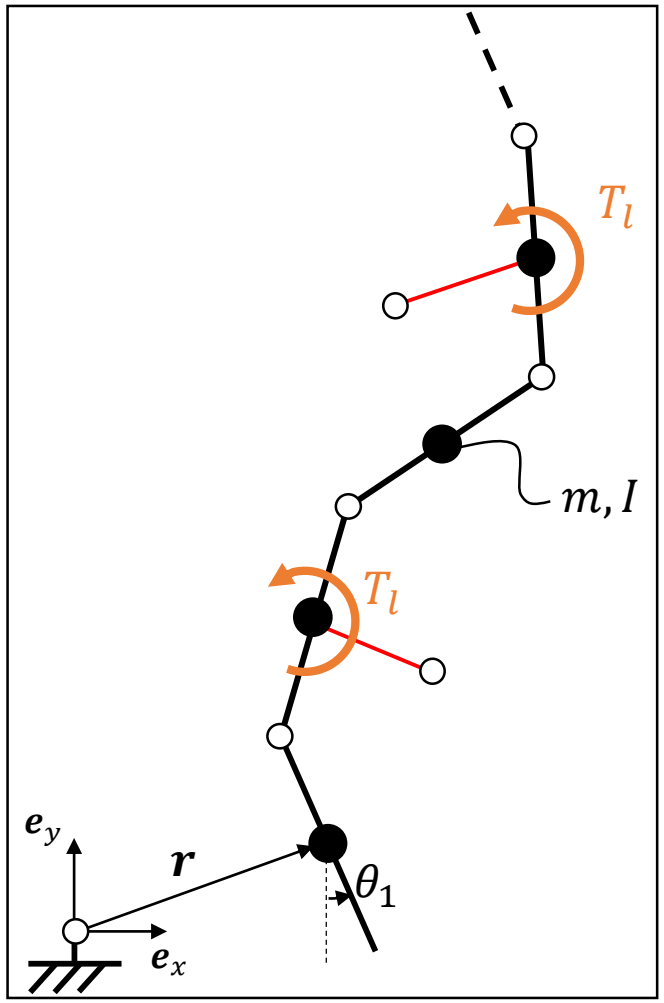


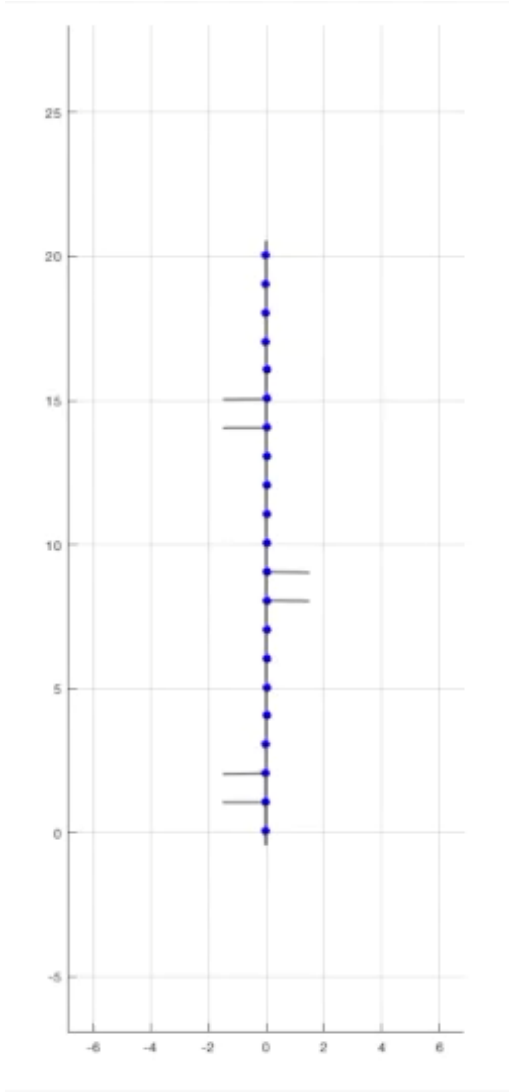

S. M. Manton, Zool. J. Linnean. Soc. 45 ,306-07 (1965).



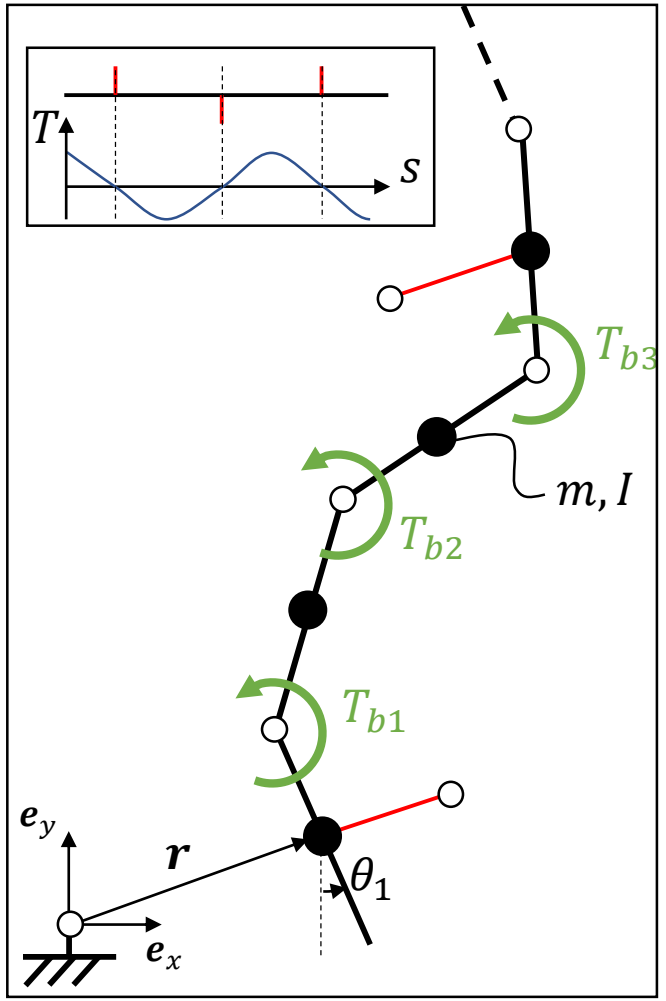



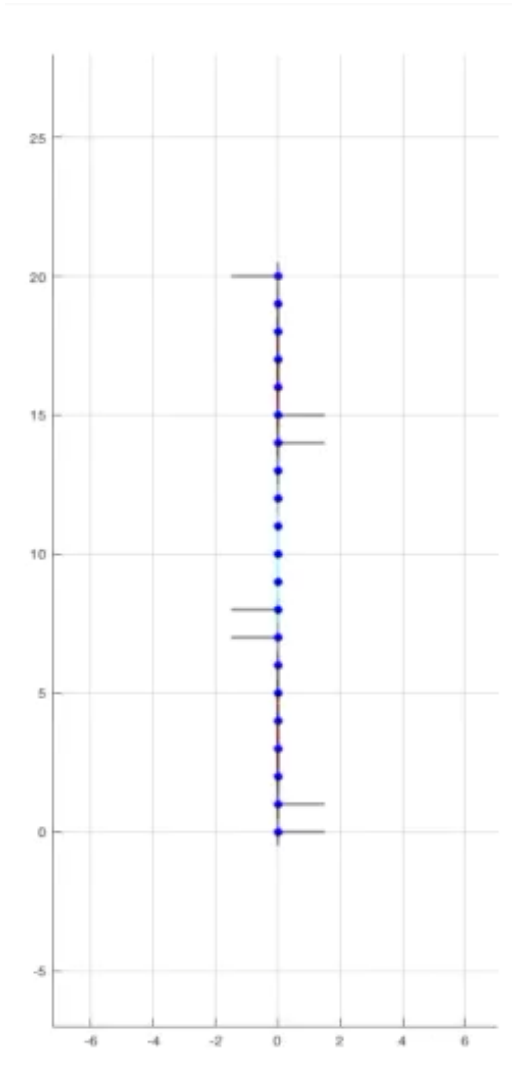
## Leg actuation



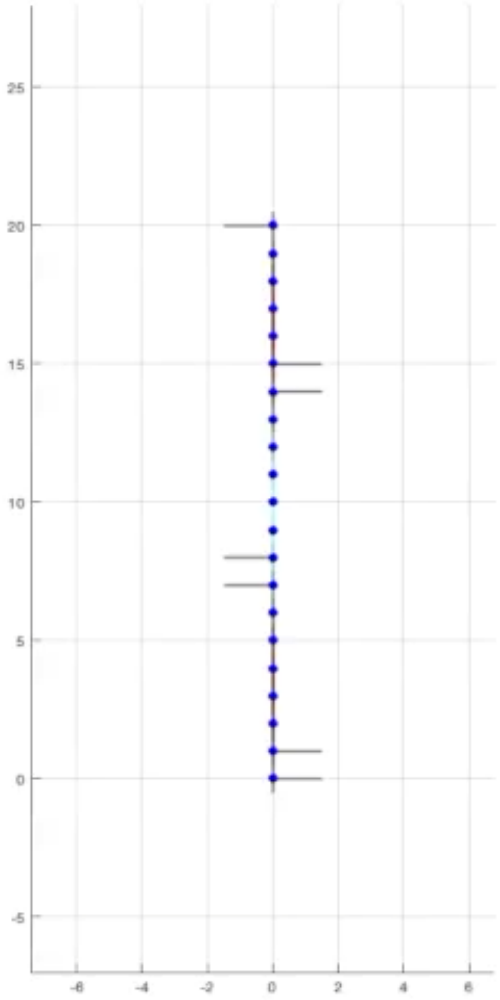



## Bending actuation

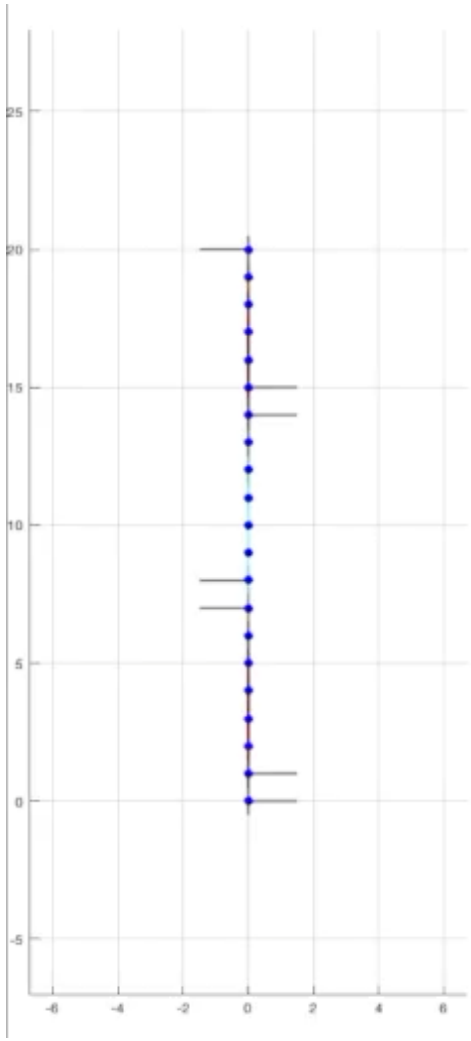


# Jamming

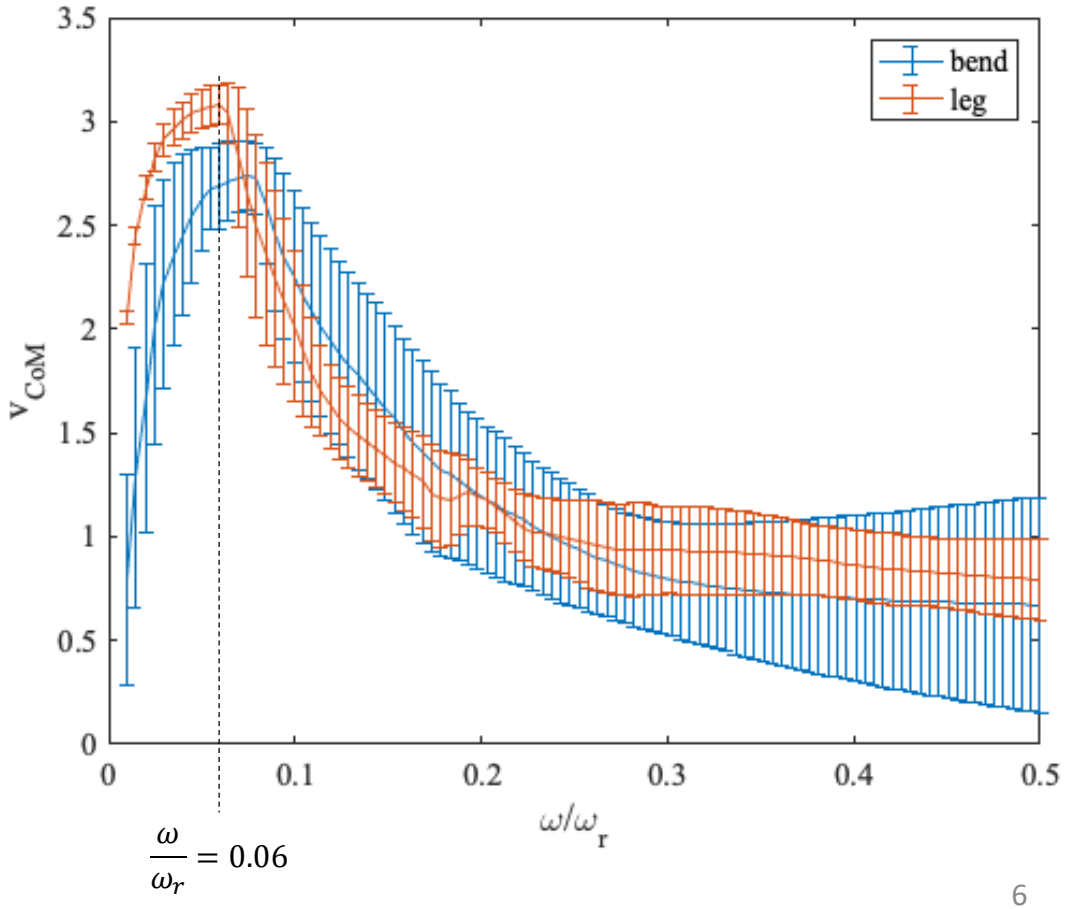


$\bar{k} = 0, \bar{d} = 0$



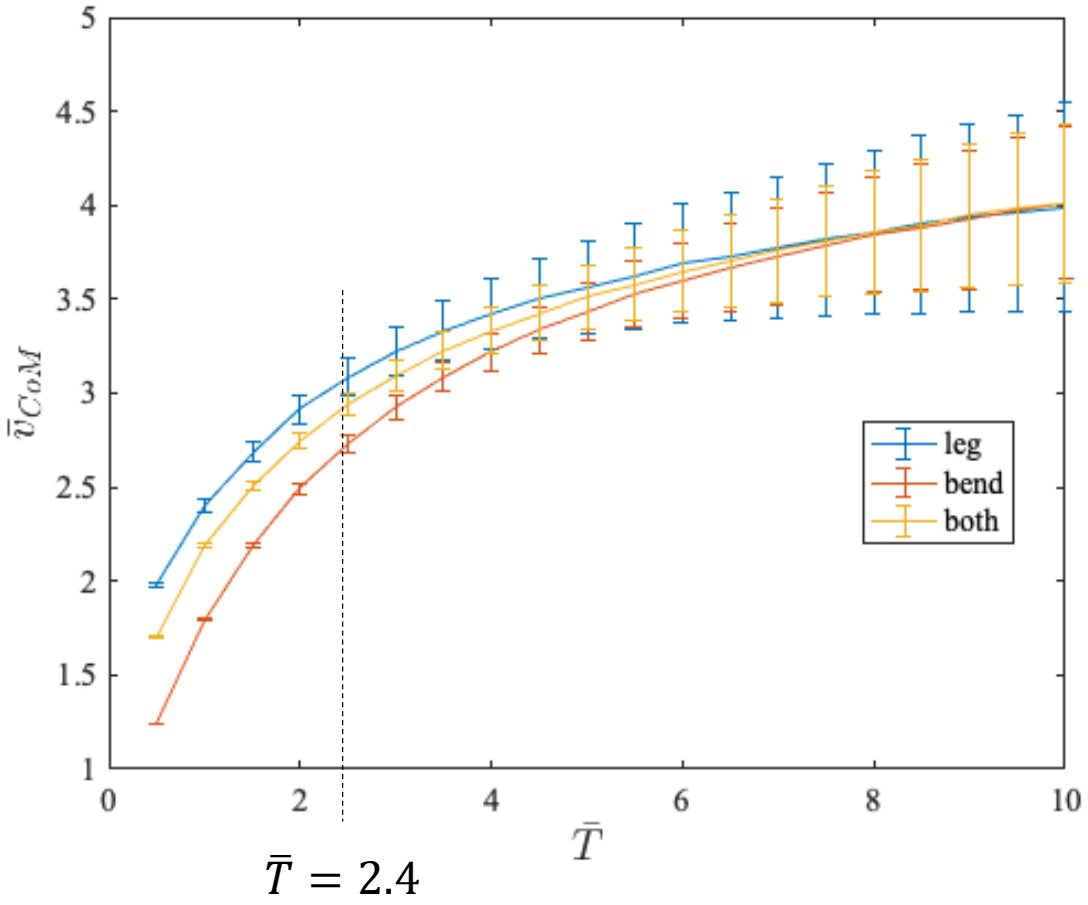
$\bar{k} = 0, \bar{d} > 0$

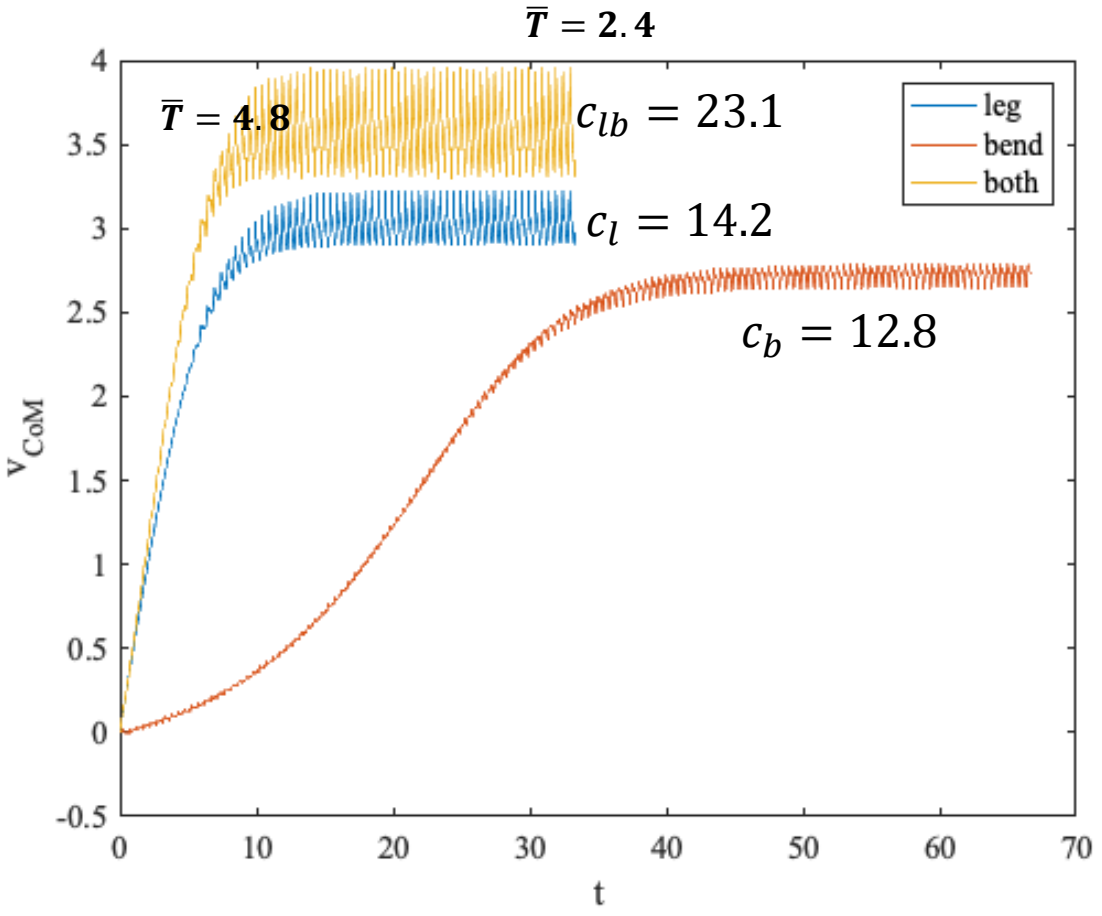
$$D = \frac{\bar{d}/2\bar{I}}{\sqrt{\bar{k}/\bar{I}}} = 3 \qquad \frac{\omega}{\omega_r} = \frac{\sqrt{\bar{T}/\bar{I}}}{\bar{d}/2\bar{I}}$$



# Superposition of actuation

Cost of transport $c = \frac{\bar{P}}{\bar{v}_{CoM}}$



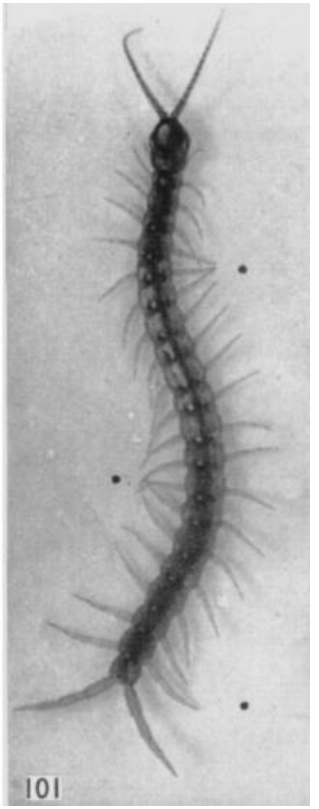
# Conclusion

- (Manton, 1977): Undulations are due to stepping pattern and deleterious[1]

➢ Undulations emerge by imposing stepping patterns
➢ Actively resisting undulations (high stiffness) leads to lower locomotion speed

- (Anderson, 1995): Undulations actively supported by muscles[2]

➢ Superimposing active bending on legged actuation increases speed and acceleration
➢ …but is energetically inefficient




1 S. M. Manton, Oxford: Clarendon Press (1977).
2 B. D. Anderson, J. W. Shultz, and B. C. Jayne, J. Exp. Biol. 198, 1185 (1995).